



Stability assessment of jointed rock slope with different crack infillings under various thermomechanical loadings

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Abstract

Thermoelastic deformation of rock significantly affects the stability of rock slope because thermoelastic strains may cause fracture propagation under favorable condition of failure. Rock slope stability depends on the balance between shear stress and shear resistance along the plane of weakness. Due to warming of rock slopes by heat transfer phenomena, viz. conduction and convection, considerable change in induced stresses (normal and shear) and resistance takes place which further causes instability in rock slope. In this paper, a two-dimensional finite element model has been used to simulate the stability of jointed rock slope containing crack in its upper surface. Four different cases have been simulated on the basis of infilling material (air, water, ice, water and ice) in the crack. Stability of rock slope is examined in terms of shear displacement and factor of safety for different thermal conditions of slope surface. A comparative study has been done for the four cases of infilling material in the crack. The various affecting parameters, viz. shear displacement, factor of safety, shear strength along the joint, and different surface temperature conditions, are illustrated by means of graphs. It has been found that the values of horizontal and vertical displacements are in the range of millimeters. The maximum values of horizontal and vertical displacements are 2.17 mm. Moreover, the maximum values of vertical compressive and tensile stresses are 15.4 MPa and 4.45 MPa respectively for the said four cases. According to the infilling material in the crack, the stability of the rock slope for the given geometry of slope is found in the following order: crack filled with ice < crack filled with ice and water < crack filled with water < empty crack. Validations of numerical results have been done from previous studies, and it has been found that the trends of normal stress, shear strength, and shear displacement along the joint are well matched.

Keywords Factor of safety · Ice-filled crack · Rock joint · Crack · Shear strength

Abbreviations

2D FE	2-Dimensional finite element
σ_n	Normal stress along the joint
σ_s	Shear stress along the joint
u_{normal}	Normal displacement along the joint
u_{shear}	Shear displacement along the joint
τ	Shear strength along the joint
FOS	Factor of safety
Z	Depth of crack

W	Width of crack
E_r	Elastic modulus of rock
ρ_r	Density of rock
ν_r	Poisson's ratio of rock
k_r	Thermal conductivity of rock
α	Coefficient of thermal expansion for rock
c_p	Specific heat at constant pressure for rock
ϕ	Friction angle for rock
σ_t	Tensile strength of intact rock
σ_c	Compressive strength of intact rock
c	Cohesion for rock
E_i	Elastic modulus of ice
ν_i	Poisson's ratio of ice
ρ_i	Density of ice
k_i	Thermal conductivity of ice
c_p	Specific heat for ice
γ	Ratio of specific heat for ice
α_i	Coefficient of thermal expansion for ice

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h_a	Convective heat transfer coefficient for air
h_w	Convective heat transfer coefficient for water

Introduction

Thermoelastic stresses may lead to fracture propagation when conditions are favorable for failure. Thermoelastic stresses give rise to strains in the presence of lateral temperature variation, topography, and material heterogeneity (Erismann and Abele 2013; Harrison 1976; Harrison and Herbst 1977). Thermal fatigue may cause permanent crack displacements in the rock slope (Mufundirwa et al. 2011). Unstable blocks of a certain volume formed in the slopes by the intersection of discontinuities and move downhill due to cyclic thermomechanical process (Watson et al. 2004). Fereidooni (2017) examined the influence of discontinuities and clay minerals in their filling materials on the instability of rock slopes. Jiao et al. (2015) simulated thermal rock cracking induced by thermal effects with the help of a coupled thermomechanical discontinuum model.

The presence of ice in the rock slope can increase shear stress due to cryostatic pressure, i.e., by ice segregation. Adler and Thovert (1999) observed that the presence of fracture affects the rock mass strength and increases the entry of water, which may lead to significant reduction in stability. The strength of the steep rock slopes reduces drastically due to the melting of ice filled in the cracks and the subsequent buildup of hydrostatic pressure (Haerberli et al. 1997). Several researchers examined that as the temperature increases, the frozen rock joints become unstable before thawing, which is the zone of minimum stability (between -1.5 and 0 °C) (Davies et al. 2001; Grämige et al. 2017). The melting of ice filled in the crack of the rock slope may result in fatal accidents due to both extreme rockfall activity and slow rock slope deformation due to thermomechanical stresses (Krautblatter et al. 2013). When the ice changes into water due to phase change, there may be two possibilities. First, there may be breaking of the joint bond which is due to ice/rock interlocking and adhesion of the ice to the rock. The other may be the enhanced water pressure in the joint due to the release of water in undrained condition. This enhanced water pressure leads to a reduction in the effective normal stress in the joint which causes a decrease in the shear strength of the rock joint (Davies et al. 2001). Bilgin and Pasamehmetoglu (1990) investigated the shear behaviour of shale joints under different thermal conditions by direct shear test.

Wegmann and Gudmundsson (1999) studied the strains developed in the rock due to freezing of water. Matsuoka (2001) observed the opening of fracture because of freezing of pore water inside the rocks. Several studies show that many of the rockfalls occur due to thawing of fractured rock during frequent and/or seasonal freezing (Rapp 1960; Church et al.

1979; Douglas 1980; Fahey and Lefebure 1988; Matsuoka 1991). Ishikawa et al. (2004) and Loew et al. (2017) monitored the length of the crack on the surface of andestic bedrock to see the effect of temperature, and they reported that the combination of liquid water infiltration into crack tip and subsequent freezing is a major cause of brittle rock failure. Fischer et al. (2010) also investigated the effect of increased hydrostatic pressure due to a perched water level sealed by permafrost (Krautblatter and Hauck 2007; Krautblatter et al. 2010).

It is well known that the presence of ice in discontinuities maintains the stability of rock slopes (e.g., Bjerrum and Jrstad 1968), but there may be chance of toppling and deep-seated failure due to a reduction in rock slope stability caused by the melting of ice in the joints (Dramis et al. 1995). It has been found from several studies that the strength and stiffness of ice are functions of temperature (Penn and Meyerson 1992; Weeks and Assur 1967; Sun et al. 2013). Several tests (Barnes et al. 1971; Fish and Zaretsky 1997) conducted under controlled testing conditions manifest that both stiffness and strength of ice decrease with the increase in temperature. Davies et al. (2000) validated this result by conducting a series of direct shear tests in the laboratory with rock joint specimens. As the ground temperature increases either due to variation in seasonal temperature or warming, there may be a significant reduction in the shear resistance of ice-bonded discontinuities. This results into degradation of safety factor of the rock slope. As a result of this, the rock slope, in this case, becomes more vulnerable to failure than the rock slope where variation of temperature is insignificant.

Due to increasing activity of rock slope failure, rock slope containing ice-filled crack received much more attention from many researchers from the past few decades. It has been assumed that the distribution of permafrost affects the stability of the rock slopes and shows a quick response to temperature variations (Fischer and Huggel 2008; Fischer et al. 2010). In addition, rock slope stability is influenced by permafrost dynamics due to increase in shear stress and reduction in shear strength. Shear stress in permafrost rocks increases because of water pressure and ice segregation (reduction in shear strength).

In the present study, the complex phenomena of joint behavior under different infilling conditions has been investigated. A two-dimensional numerical model of rock slope with a crack in the upper surface of the slope has been considered for the analysis. The rock slope stability along the rock joint on different climatic scenarios is simulated using finite element-based COMSOL software (COMSOL Multiphysics Modeling Guide, version 5.2.). The stability of the rock slope is investigated in terms of factor of safety, shear displacement, and shear stress along the joint for different thermal conditions. The factor of safety for different physical scenarios viz. the crack is filled with dry air only, the crack is filled with water

only, the crack is filled with ice only, and when both water and ice present in the crack are calculated from comparative analysis of the stability of the rock slope along the joint in different thermal conditions. Moreover, the effects of hydrostatic pressure developing in the crack and heat transfer on the factor of safety of jointed rock slope are also investigated by simulation of the proposed model.

The model approach

In the present model, the factor of safety has been determined to examine the stability of jointed rock slope containing crack and single joint with a dip angle of 45° on the upper surface of the slope. The factor of safety (FOS) along the joint has been calculated by a well-known relationship between shear strength and shear stress as (Davies et al. 2001)

$$\text{FOS} = \frac{\text{Shear strength}}{\text{Shear stress}}$$

Shear strength and shear stress are evaluated with the help of global normal force and global shear force. The said normal force and shear force are the total shear and normal force acting along and perpendicular to the joint, respectively. Moreover, the global normal and shear forces along the joint are calculated using the aforementioned global normal and shear forces. The shear strength of the joint with the help of global normal stress is determined by the Mohr-Coulomb criterion as follows:

$$\tau = C + \sigma_s \tan \phi \quad (1)$$

The factor of safety along the joint of the rock slope is significantly influenced if the crack in the rock slope contains different filling (water and ice) materials (Krautblatter et al. 2013). Different infillings (water and ice) enhance the shear stress which may cause failure of the potential sliding plane along the joint. Therefore, in the present analysis, water and ice are considered as infilling material in a vertical crack. The rock-ice mechanical approach (Krautblatter et al. 2013) has been adopted to analyze these conditions. To simplify the model, rock material is assumed to be homogeneous, nonporous, and elastic. In the present study, simulation of the 2-dimensional finite element (2D FE) model consists of three components: rock mass, discontinuity, and infilling material in the crack has been carried out. The four different infilling conditions in the crack—(a) crack is filled with dry air only, (b) crack is filled with water only, (c) crack is filled with both water and ice, and (d) crack is filled with ice only—have been considered (Fig. 1).

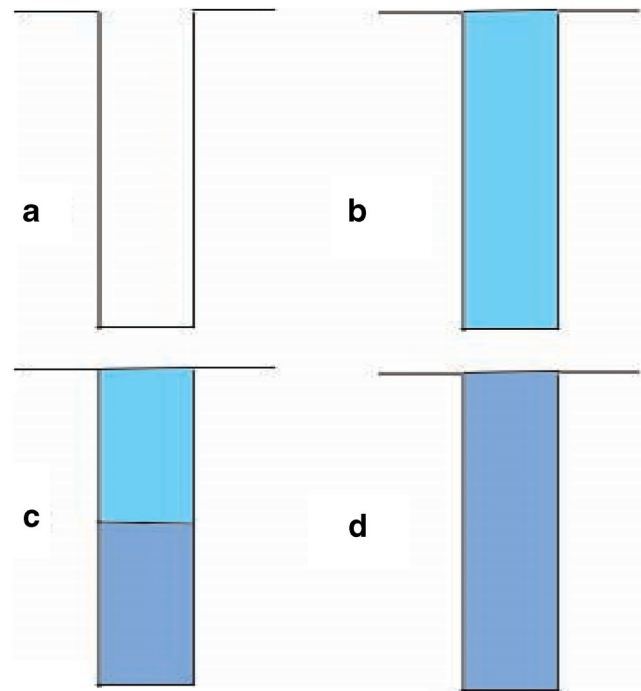


Fig. 1 Schematic diagram of the crack filled with **a** air, **b** water, **c** water and ice, and **d** ice

Case I: Crack filled with air

Conductive heat transfer in rock mass is affected by advective heat transfer due to air present in the crack. When air is filled in the crack, the flow of heat occurs in a convective way due to the seasonal temperature fluctuations (Moore et al. 2011). The variation in density and pressure results in natural circulation of air in days or years. Due to change in convective heat flow by air circulation, the temperature of the crack in the rock slope decreases in winter and increases in summer. The various affecting parameters, viz. gravity thermal expansion of jointed rock mass, cohesion of rock-rock joint, and friction between rock-rock joint, may be used to examine the mechanical behavior of rock mass. Thus, shear stress in the expression of factor of safety is induced in the rock slope due to gravity stress and thermal loading. Therefore, the equation for factor of safety can be written as

$$\text{FOS} = \frac{\tau_{sf}}{\tau_g + \tau_t}, \quad (2)$$

where τ_{sf} is the shear strength or resistance along the joint due to friction, and τ_g and τ_t are induced shear stresses along the joint due to gravity loading and thermal loading, respectively, because of warming of the slope.

Due to conduction and convection phenomena in the rock, the transfer of heat can occur up to larger depths causing thermal stress and strain (Moore et al. 2011). Gischig et al. (2011a, b) observed this type of phenomenon in Randa rockslide.

Case II: Crack filled with water

In this study, rock has been considered as a nonporous medium and the presence of water is assumed in the crack only. Since the crack is closed at the bottom point, therefore, there is no flow of water in the crack. Due to temperature difference between water and crack, the transfer of surface heat can occur through convection. The presence of water in the crack generates a hydrostatic pressure on the walls of the crack. Therefore, as the temperature increases, the shear stresses are induced in the rock slope due to the gravity force, hydrostatic pressure, and thermal stress (due to nonlinear temperature gradient). In view of this, the equation for factor of safety becomes

$$\text{FOS} = \frac{\tau_{\text{sf}}}{\tau_{\text{g}} + \tau_{\text{t}} + \tau_{\text{h}}}, \quad (3)$$

where τ_{sf} is the shear resistance due to friction along the joint, and τ_{g} , τ_{t} , and τ_{h} are induced stresses due to gravity, warming of rock slope (thermal stress), and hydrostatics pressure due to water. The permeability of discontinuity in rock mass is higher than the pore system and depends on roughness, aperture size, and infilling material (Dietrich et al. 2005). To simplify this model, chert rock mass is considered in which discontinuity is impermeable, and no filling material is present in discontinuity.

Case III: Crack filled with ice

When the crack is filled with ice, the flow of heat occurs from rock mass to ice by conduction mode of heat transfer. As warming occurs, the temperature of the surrounding and rock slope increases gradually. The temperature of ice in the crack has a significant effect on the stability of the jointed rock slope. In case when temperature is more than subzero temperature, ice in the crack is converted to water and sufficient heat is absorbed in this process from the surrounding rock which may cause induced stresses along the joint. The shear strength of ice-filled crack in the jointed rock mass is a function of both temperature and normal stress, and declines with increase in temperature (Davies et al. 2000, 2001, 2003; Günzel 2008). Krautblatter et al. (2013) developed an empirical relationship which shows failure along rock-ice contacts with the help of several experiments, and developed a relationship between creep deformation of ice and temperature. The shear stress induced along the joint is due to gravity force, thermal stress, and enhanced water pressure due to melting of ice. The equation of factor of safety for the case when the crack is filled with ice becomes

$$\text{FOS} = \frac{\tau_{\text{sf}} + \tau_{\text{i}}}{\tau_{\text{g}} + \tau_{\text{t}} + \tau_{\text{h}}}, \quad (4)$$

where τ_{sf} is the shear strength for rock-rock contact and τ_{i} is the shear strength for rock-ice contact present in the crack. τ_{g} , τ_{t} , and τ_{h} are induced stresses due to gravitational pull, thermal loading due to warming, and hydrostatic pressure due to melt water present in the crack.

Case IV: Crack filled with both ice and water

If the crack is filled with both ice and water, then as the temperature of rock slope increases, ice gets converted into water and heat is absorbed in this process. Water transports heat in a conductive way ($k = 0.5 \text{ W m}^{-1} \text{ K}^{-1}$) when it is static and also in a convective way due to density difference after heating. The ice in the crack melts as the temperature rises. As a result of this, the shear strength of the rock gets significantly influenced. The presence of water columns in the crack creates hydrostatic pressure on the walls of the crack. Therefore, mobilizing (shear) stress is induced due to gravity, thermal stress, and increased water pressure due to melting of ice. The equation of factor of safety, in this case, can be written as

$$\text{FOS} = \frac{\tau_{\text{sf}} + \tau_{\text{i}}}{\tau_{\text{g}} + \tau_{\text{t}} + \tau_{\text{h}}}, \quad (5)$$

where τ_{sf} is the shear strength for rock-rock contact and τ_{i} is the shear strength for rock-ice contact present in crack. τ_{g} , τ_{t} , and τ_{h} are induced stresses due to gravitational pull, thermal loading due to warming, and hydrostatic pressure due to melt water present in the crack.

Two-dimensional finite element analysis

Governing equations

Heat transfer

In this study, the heat transfer interface is used for the transfer of heat in the rock medium. The following equation is used to simulate the heat transfer phenomena

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q, \quad (6)$$

where ρ is the density of the medium, C_p is the specific heat capacity at constant temperature, T is the absolute temperature, u is the velocity vector, k is the thermal conductivity of the medium, and Q is the heat source other than the viscous heating. For flow of heat (out of plane) through boundaries of the slope, convective heat flux (out of plane) is used at boundaries of the model. The following equation governs the heat transport phenomenon through boundaries

$$-\mathbf{n} \cdot (-k \nabla T) = h \cdot (T_{\text{ext}} - T), \quad (7)$$

where \mathbf{n} is the vector normal to the boundary, k is the thermal

conductivity, h is the effective convective heat transfer coefficient, T_{ext} is the temperature of the outer of the boundary, and T is the temperature of rock. The convective heat flux (out of plane) is used for heating or cooling of homogeneous elastic rock material. For the transfer of heat along the joint, temperature gradient is assumed to be negligible across the walls of the rock joint. The following boundary condition is used to simulate the joint behavior

$$-\mathbf{n} \cdot (-k \nabla T) = 0 \tag{8}$$

where \mathbf{n} is the vector normal to the walls of the joint, k is the thermal conductivity, and T is the absolute temperature.

Deformation of elastic rock matrix

Total strain tensor generated in the linear elastic material is given as

$$\varepsilon = \frac{1}{2} [(\nabla \cdot \mathbf{u})^T + (\nabla \cdot \mathbf{u})], \tag{9}$$

where ε is the strain tensor and u is the displacement.

Duhamel-Hooke’s law is used to relate the total strain tensor with stress tensor and temperature

$$s - s_0 = C : (\varepsilon - \varepsilon_0 - \alpha \theta), \tag{10}$$

where s is the induced stress tensor, s_0 is the initial stress tensor, C is the elasticity tensor of fourth-order, “:” indicates the double-dot tensor product, ε is the total induced strain tensor, ε_0 is the initial stress tensor, α is the thermal expansion tensor, and $\theta = T - T_{ref}$. Following are the basic equations of equilibrium used to evaluate unknown variable field

$$\sigma = s, \tag{11}$$

$$\nabla \cdot \sigma = F_v, \tag{12}$$

where F_v is the external body force and s is the stress tensor evaluated from Duhamel-Hooke’s law.

For contact friction modeling in FEM, the source and destination boundaries of the rock joint are specified and then defined via contact elements. After that, these elements describe kinematics of deformation. The joint in the rock slope is simulated using penalty contact algorithm in which contact springs are being used to establish a relationship between two contact boundaries. The friction along the rock joint is defined by standard Coulomb friction algorithm (Eq. 1) given as

$$\tau = c + \sigma_n \tan \phi, \tag{13}$$

where τ is the shear resistance (strength) along the joint, c is the cohesion between walls of joint, σ_n is the normal stress to the joint, and ϕ is the friction angle. The standard unilateral contact surface mode is used in which the contact pressure becomes zero after separation. Normal stress and shear stress

can be calculated using the following equations

$$\sigma_n = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{xy} \sin 2\theta \tag{14}$$

$$\sigma_s = \frac{\sigma_x - \sigma_y}{2} \sin 2\theta + \tau_{xy} \cos 2\theta \tag{15}$$

where σ_n and σ_s are the normal and shear stress along the joint, σ_x and σ_y are the components of the stress tensor along the x and y directions, τ_{xy} is a shear component of stress tensor, and θ is the angle of dip of joint. From shear resistance and shear stress along the joint, the factor of safety can be evaluated using the following equation

$$FOS = \frac{\text{Shear strength}}{\text{Shear stress}}$$

Shear displacement and normal displacement along the joint can be calculated from the following equations

$$u_{\text{normal}} = u_x \sin \theta + u_y \cos \theta \tag{16}$$

$$u_{\text{shear}} = u_x \cos \theta - u_y \sin \theta \tag{17}$$

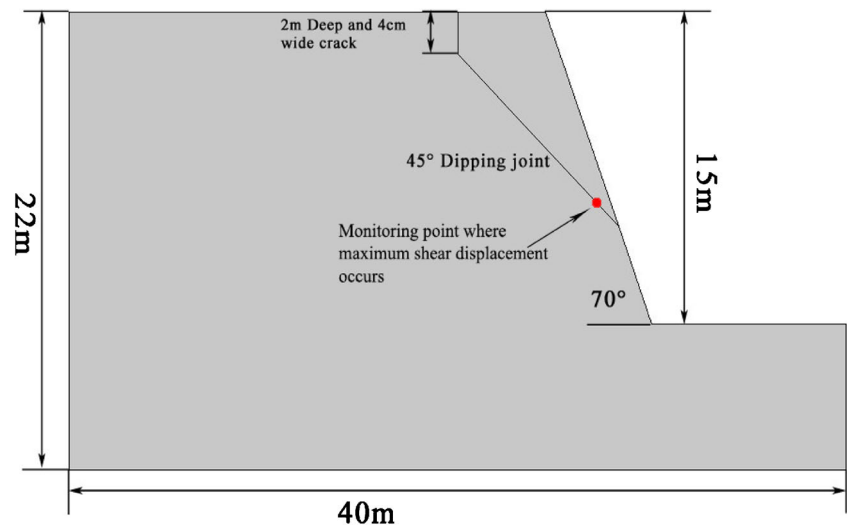
where u_{normal} and u_{shear} are normal and shear displacements along the joint, u_x and u_y are the components of total displacement in x and y directions, and θ is the angle of dip of joint.

Finite element model

Factors influencing rock slope deformation which is affected by thermomechanical forcing are simulated using 2D FE analysis. The purpose of the study is to examine the process of failure along the joint under thermomechanical stresses. The magnitude of induced displacements, thermomechanical stresses, and factor of safety along the joint has also been investigated. Numerical simulation of a crack (with the different infilling materials) of 2 m depth on the upper surface of the jointed rock slope under temperature variation has been done. The model contains a homogeneous elastic media with a single discontinuity. Discontinuity is simulated with shear properties like cohesion, friction angle, etc. The value of tensile strength is high enough so that failure of joint does not occur under the influence of tensile stress. On the other hand, shear failure is described according to the Mohr-Coulomb criteria, in which after slip, cohesion becomes zero and only friction force acts.

In the simulation scheme, a two-dimensional model of rock slope (20m height) has been considered (Fig. 2). Discontinuity in slope is considered from the tip of the crack with a dip angle of 45°, while the face of the slope is assumed to be dipped by an angle of 70°. Initial equilibrium condition is simulated by applying gravity to all domains of the slope for the case of initial stresses due to gravity. Positive temperature variation (0–13 °C) has been taken to study the effect of thermal load on the walls of

Fig. 2 Geometrical specification of rock slope used for 2-dimensional finite element analysis



the joint. The physicommechanical properties are given in Table 2. Ice filled in the crack first changes to water (exchange heat according to the latent heat of fusion), with further increase in temperature after a change of ice phase heat, and is transferred in a convective way from the rock to water.

A 2D FE model is analyzed using plain strain condition to simulate in situ condition. The extra fine mesh is used to minimize meshing error with 5331 triangular elements and 23,158 nodes as shown in Fig. 3. To simulate heat transfer across the joint, continuity boundary condition is used in which temperature gradient perpendicular to the walls of discontinuity is set to zero, i.e., the same temperature is considered on the source and destination boundaries. Rock joint is simulated with the penalty contact method. Frictional and cohesive conditions are used along the

boundaries of the joint. Thermal displacement has been calculated using elastic analysis. Tensile stress is considered as positive (+) and compressive stress is taken as negative (–) in the numerical analysis. Two physics solid mechanics and heat transfer in solids are coupled to solve the thermomechanical problem. To simulate heat transfer between a rock and infilling material (air, water, and ice) in the crack, a convective heat flux is used in which initial temperature of the infilling material column is considered to be 0.15 °C.

Thermomechanical boundary conditions

Numerical simulations are performed for the four cases (based on infilling material) at different thermal conditions. These all

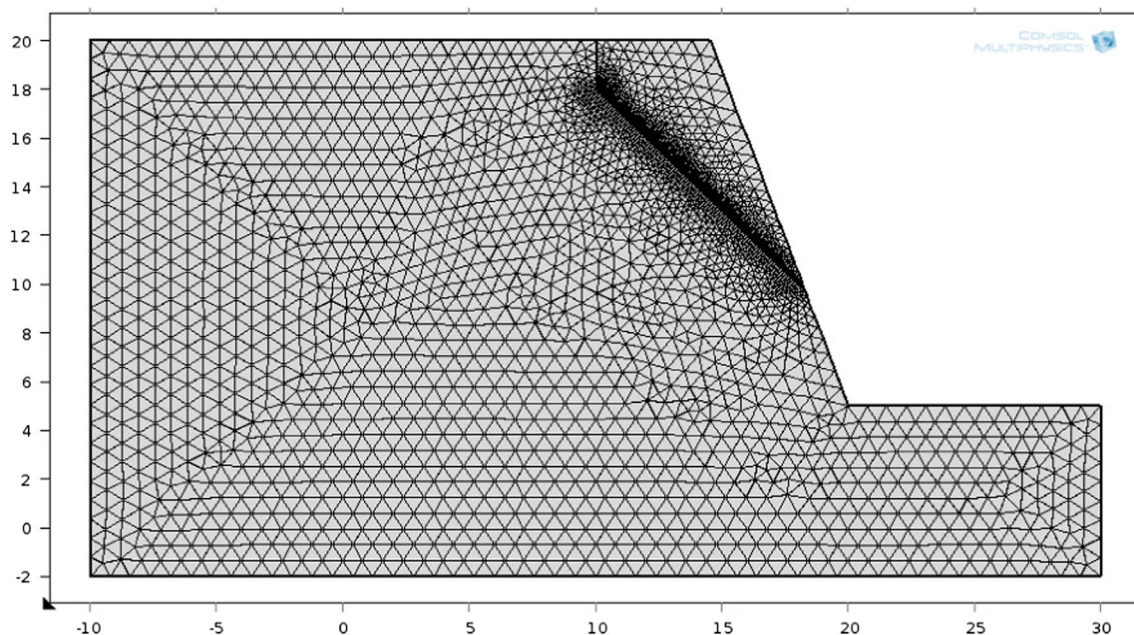


Fig. 3 Finite element mesh configuration for solid mechanics study used in the numerical simulation for confined boundary conditions

are the elastic analyses under confined boundary conditions. In solid mechanics physics, vertical boundaries in the numerical model are constrained with roller boundary condition and the bottom boundary of the slope is fixed. The initial temperature of the model is fixed at 0.15 °C to simulate heating condition. A convective heat flux with heat transfer coefficient equal to air and with external temperature (temperature of the surrounding air) of magnitude T is applied to the outer boundaries of the slope, while boundaries which are far away from the discontinuity are considered to be at a temperature of 0.15 °C equal to the temperature of the ground. Rock is considered initially at 0.15 °C temperature and then the temperature is increased up to 13.15 °C for all the cases. Rock mass is considered to be homogeneous and isotropic for the simulation (Fig. 4).

Input parameters used for numerical analysis

The following physicommechanical properties are used to simulate the conditions given in the model (Tables 1 and 2).

Numerical results and discussion

Extensive analysis of the numerical model shows the variation of rock slope temperature under the influence of the slope surface temperature field (Fig. 5a-d). The temperature profile around the crack and along the joint has been shown in this figure. Conduction and convection heat transfer phenomena are the dominant modes of heat transfer due to solar radiation in the rock slope walls. Conductive heat transfer takes place in the rock due to a temperature gradient. Convective heat transfer takes place between the fluid (air and water) and rock surface under different thermal conditions. Temperature near the crack is low which further increases along the joint. This temperature acquires a maximum value where the joint is exposed to the surrounding environment at the slope surface (Fig. 5a-d). The temperature of

Table 1 Physicommechanical properties of jointed rock used in the numerical model

Property	Value	Unit
Elastic modulus	51.88	GPa
Density	2621.95	kg/m ³
Poisson's ratio	0.33	–
Thermal conductivity	3.12	W/m K
Coefficient of thermal expansion	6×10^{-6}	K ⁻¹
Specific heat at constant pressure	800	J/kg K
Friction angle	40°	–
Tensile strength of intact rock	8×10^6	N/m ²
Compressive strength of intact rock	40×10^6	N/m ² F
Dip	40°	–
Cohesion	0.7×10^5	N/m ²

the exposed surface in all four cases viz. crack filled with dry air (Fig. 5a), crack filled with water (Fig. 5b), crack filled with ice (Fig. 5c), and crack filled with both water and ice (Fig. 5d) is varied from 0 to 13.15 °C with an initial temperature of the slope being 0.15 °C. The values of maximum displacements (horizontal and vertical) and stresses (vertical and horizontal) are found in the order of millimeters and megapascals respectively. The little variation in the maximum values of said displacements and stresses is observed. Figures 6(a-d) and 7(a-d) show variation of horizontal and vertical displacements, and the arrows in the profile indicate the direction of total displacement. The values of horizontal and vertical displacements are found in the order of millimeters. The maximum values of horizontal and vertical displacements are in the range of 2.1–2.17 mm for the four physical cases viz. crack filled with air (Figs. 6a and 7a), crack filled with water (Figs. 6b and 7b), crack filled with ice (Figs. 6c and 7c), and crack filled with both ice and water (Figs. 6d and 7d) at the surface temperature of 13.15 °C. These values of displacements are due to thermal loading caused by nonlinear temperature field gradient and gravitational loading. The nonlinear temperature gradient in the slope produces expansion,

Fig. 4 Thermomechanical boundary conditions used for numerical simulation

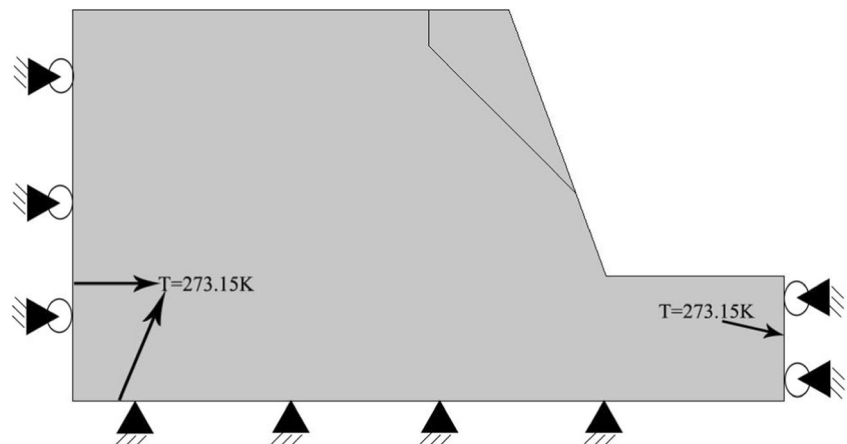


Table 2 Physicomechanical properties of infilling material (ice, air, water) in the crack used to simulate the numerical model (De Blasio 2014; Barker and Timco 2003; Bergman et al. 2011)

Property	Value	Unit
Elastic modulus	8.7	GPa
Poisson's ratio	0.31	–
Density	917	kg/m ³
Thermal conductivity	2.1	W/m K
Specific heat	2093	J/kg K
Ratio of specific heat	1	–
Coefficient of thermal expansion of ice	1.8×10^{-7}	K ⁻¹
Frictional angle for rock-ice contact	2.862°	–
Cohesion for rock-ice contact	364	kPa
Convective heat transfer coefficient for air	23	w/m ² •K
Convective heat transfer coefficient for water	123	w/m ² •K

contraction, and rotational distortions. It can be clearly seen from Figs. 6(a-d) and 7(a-d) that thermal effects are more dominant effects than loading gravitational effects. To see thermomechanical effects more rigorously, the vertical and horizontal stresses are shown through Figs. 8(a-d) and 9(a-d) respectively. The maximum value of vertical compressive stress through the domain is in the range of 15.3–15.4 MPa, for the four cases viz. crack filled with air (Fig. 8a), crack filled with

water (Fig. 8b), crack filled with ice (Fig. 8c), crack filled with ice and water (Fig. 8d) at 13.15 °C temperature of the exposed slope surface. The maximum value of vertical tensile stress through the domain is in the range of 4.38–4.45 MPa for the four cases viz. crack filled with air (Fig. 8a), crack filled with water (Fig. 8b), crack filled with ice (Fig. 8c), crack filled with ice and water (Fig. 8d) at 13.15 °C temperature of the exposed slope surface. When the temperature variation is nonlinear, the rock structure is subjected to different thermal stresses, because every rock element, being attached to other rock elements, cannot exhibit free temperature expansion. Thermal stresses in the cross section area of a statically determinate rock structure are regarded as self-equilibrating stresses. In the cross section of statically indeterminate rock structure such as continuous linear elastic homogenous rock slopes, the linear or nonlinear increment in temperature produces statically indeterminate reactions and internal forces. The stresses due to these forces are referred as continuity stresses. In most instances, continuity thermal stresses are of greater magnitude than primary thermal stresses (caused by nonlinear temperature variation). Similarly, the maximum value of horizontal compressive stress is in the range of 22.4–22.8 MPa at slope surface temperatures of 13.15 °C respectively for the four physical cases viz. crack filled with air (Fig. 9a), crack filled with water (Fig. 9b), crack filled with ice (Fig. 9c), crack filled with ice and water (Fig. 9d). The maximum value of horizontal tensile stresses caused by mechanical and thermal effects is in the

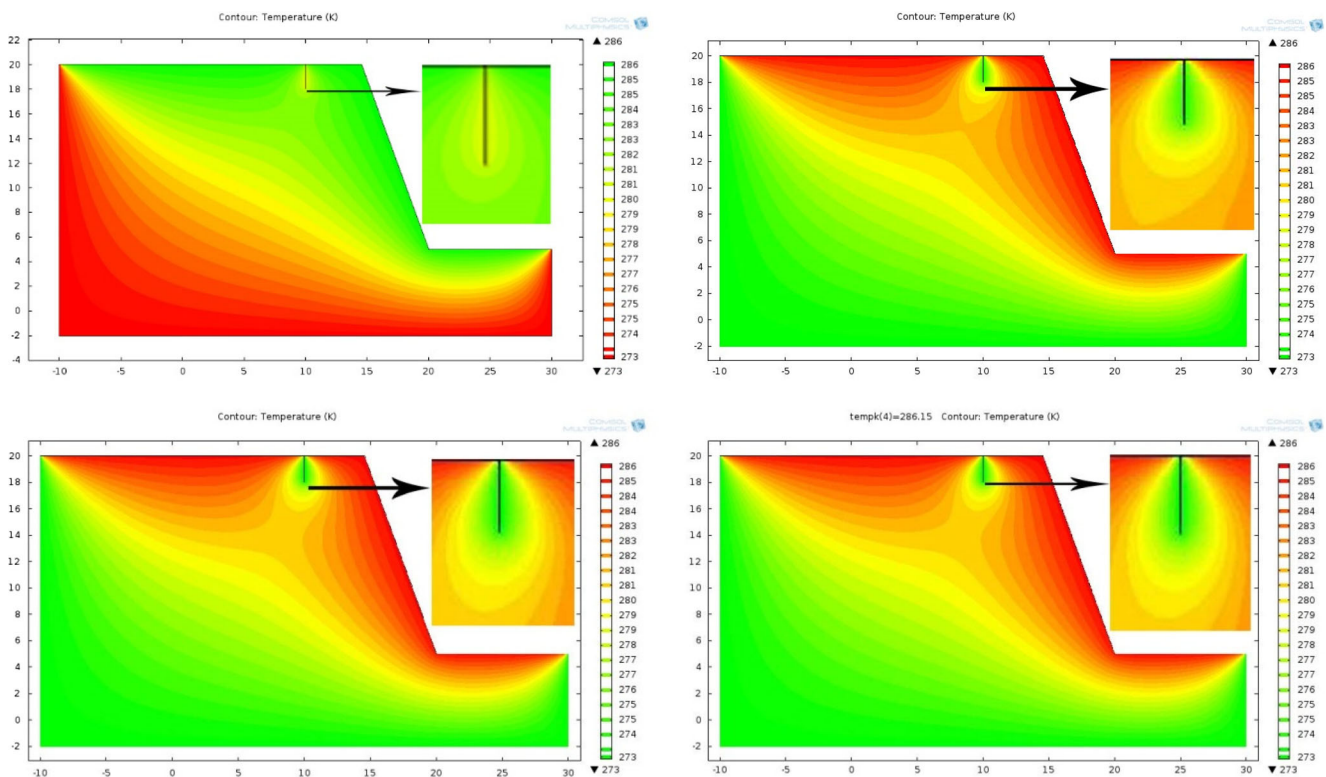


Fig. 5 a Contours of temperature when the crack is filled with dry air. b Contours of temperature when the crack is filled with water. c Contours of temperature when the crack is filled with ice. d Contours of temperature when the crack is filled with water and ice

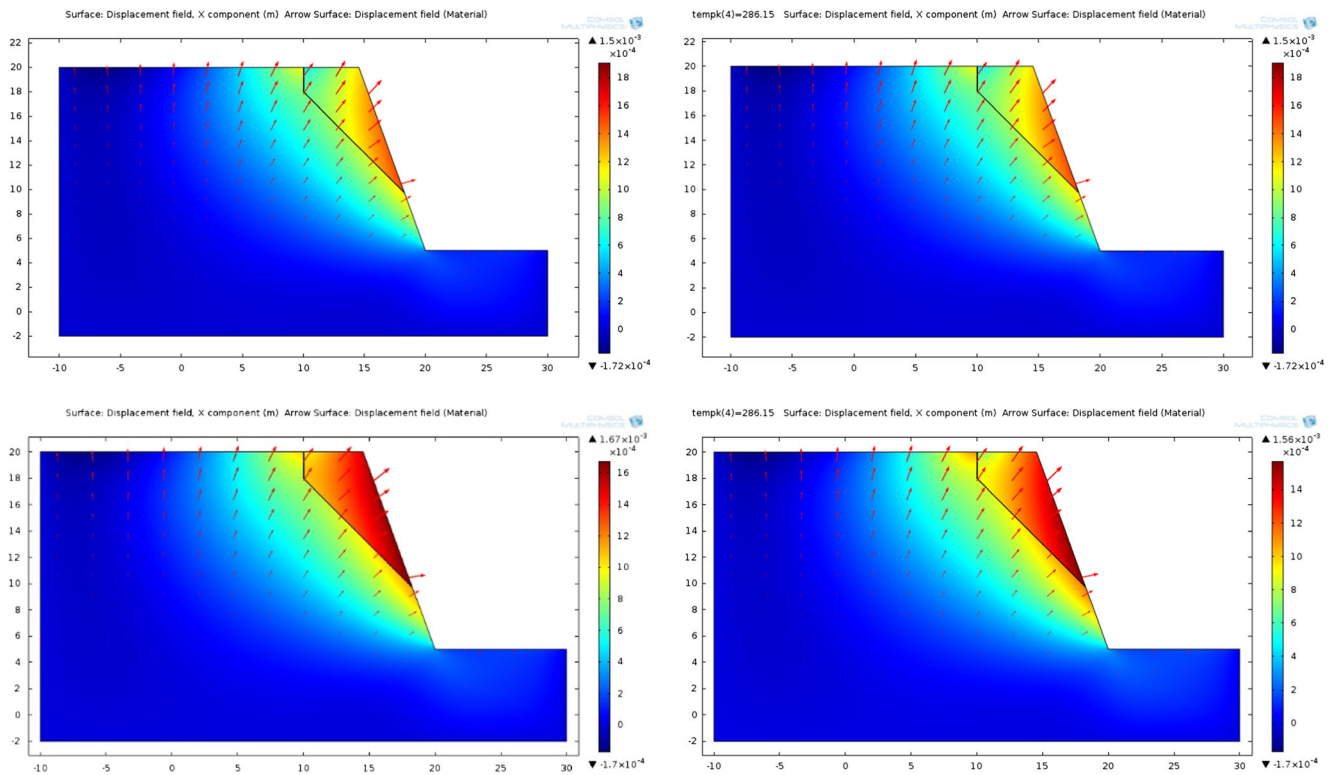


Fig. 6 **a** Contours of horizontal displacement with arrows showing the direction of total displacement when the crack is filled with dry air. **b** Contours of horizontal displacement when the crack is filled with water. **c**

Contours of horizontal displacement when the crack is filled with ice. **d** Contours of horizontal displacement when the crack is filled with water and ice

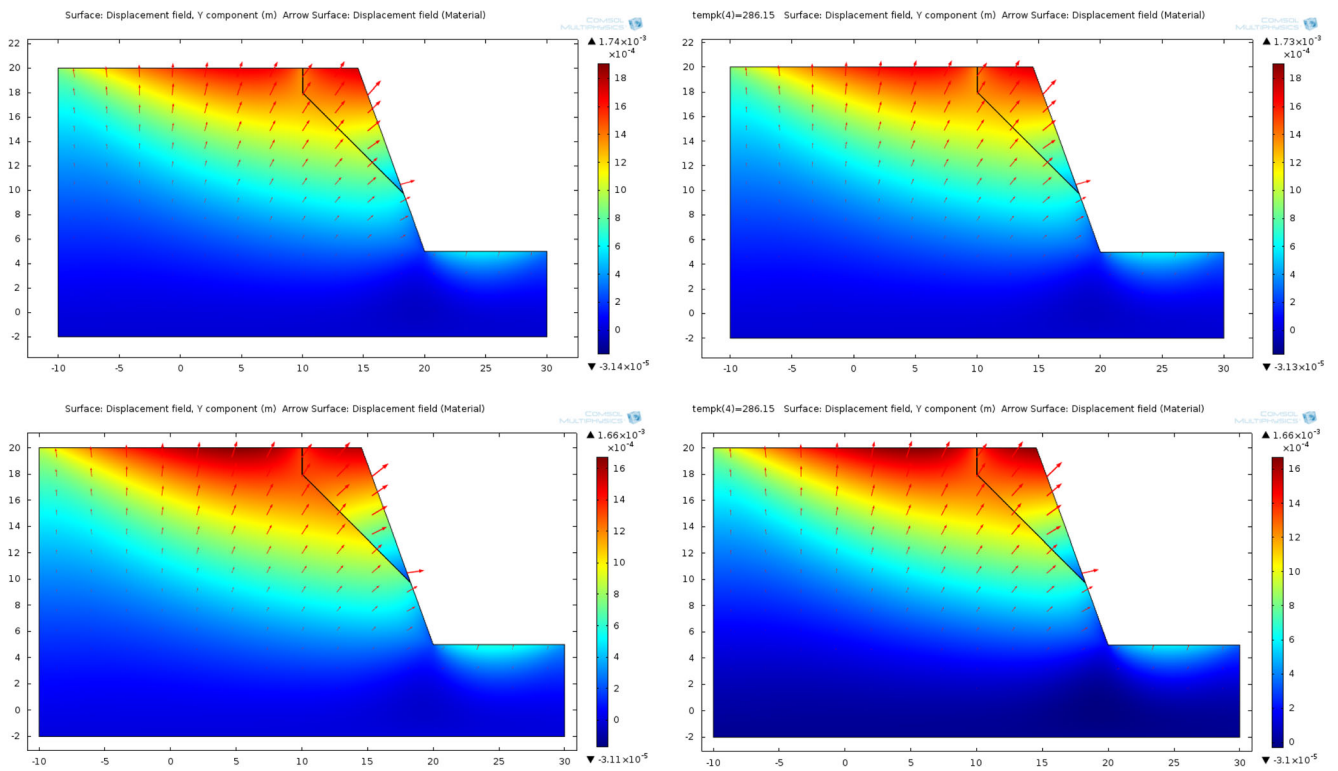


Fig. 7 **a** Contours of vertical displacement with arrows showing the direction of total displacement when the crack is filled with dry air. **b** Contours of vertical displacement when the crack is filled with water. **c**

Contours of vertical displacement when the crack is filled with ice. **d** Contours of vertical displacement when the crack is filled with water and ice

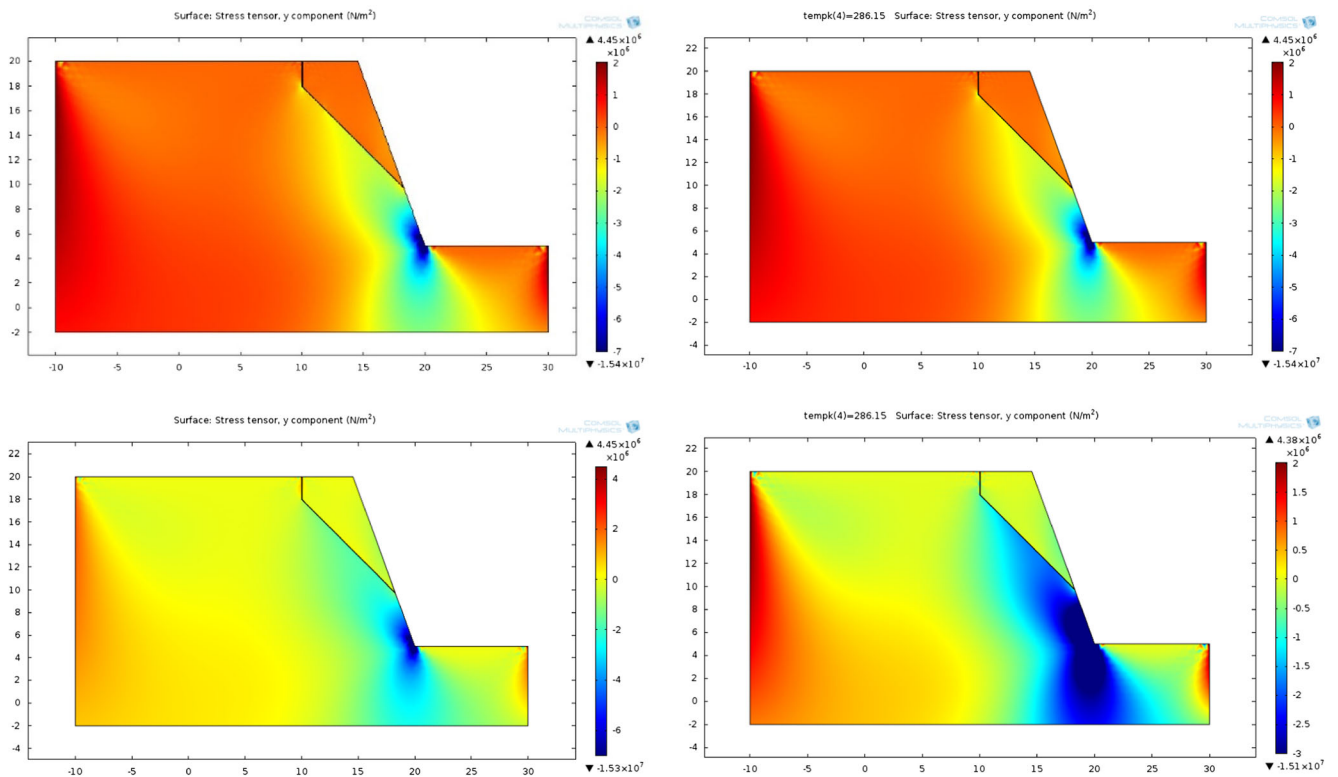


Fig. 8 a Contours of vertical stress when the crack is filled with dry air. b Contours of vertical stress when the crack is filled with water. c Contours of vertical stress when the crack is filled with ice. d Contours of vertical stress when the crack is filled with water and ice

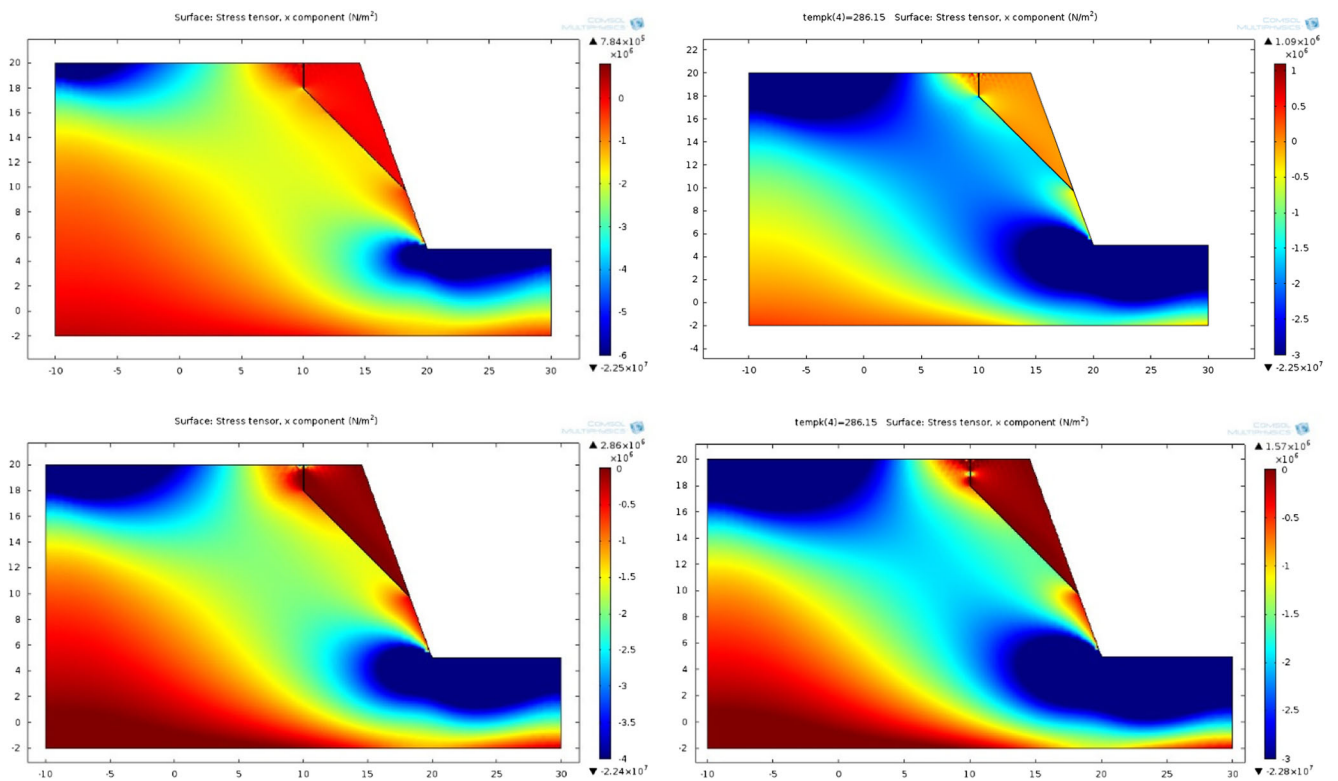


Fig. 9 a Contours of horizontal stress when the crack is filled with dry air. b Contours of horizontal stress when the crack is filled with water. c Contours of horizontal stress when the crack is filled with ice. d Contours of horizontal stress when the crack is filled with water and ice

range of 0.78–1.57 MPa at slope surface temperatures of 13.15 °C respectively for the four cases viz. crack filled with air (Fig. 9a), crack filled with water (Fig. 9b), crack filled with ice (Fig. 9c), crack filled with ice and water (Fig. 9d). As a result of this, compressive/tensile stress may cause failure in intact rock structures, but uniaxial compressive/tensile strength of the intact rock is high enough to overcome these stresses. Shear displacement along discontinuities may cause movement of unstable blocks (volume of blocks up to a few cubic meters) downhill due to thermomechanical loading.

Analysis of rock joint with FEM

Figure 5(a-d) show the results of FEM contact simulation which allows sliding along 45° dipping joint without slip weakening. Continuity boundary condition (temperature gradient which is normal to the joint and also across two boundaries of the joint is assumed to be zero) is used to simulate heat transfer across the rock joint. Due to temperature difference between the fluid (water and air) and crack surface, convective heat transfer takes place which causes a decrease in the temperature of the rock near the crack. Temperature distribution along the joint is shown in Fig. 5(a-d) at a different surface temperature of the rock slope. The temperature near the crack along the joint is less due to convective heat transfer and high at the exposed end due to less distance between the temperature source and joint. For contact friction modeling with FEM, first source and destination boundaries of the rock joint are specified and then defined via contact elements. Now, these elements will then track the kinematics of deformation. The rock joint is solved with penalty contact algorithm in which contact springs are being used to establish a relationship between two contact boundaries. The friction along the rock joint is defined by standard Coulomb friction algorithm (Eq. 1). The standard unilateral contact surface mode is used in which the contact pressure becomes zero after separation. The thermomechanical induced shear stress cause shear

displacement along the joint. Shear stress along the joint is induced according to the temperature gradient along the joint and downward gravitational pull. Progressive failure of the joint may occur through the stepwise advancement of slip fronts as a change in shear displacement which further makes a change in induced shear stresses along the joint. Figure 10 shows the variation of shear displacement along the joint at different slope surface temperatures. In this figure, the positive value of shear displacement indicates right lateral movement (movement of upper wedge in the right direction). Positive and negative values of shear displacement are due to thermal expansion of the rock according to the temperature gradient along the joint. A negative value of shear displacement shows a contraction of crack, and a positive value of shear displacement shows expansion of rock near the free exposed boundary of the slope. Point 1 is selected where maximum shear displacement along the joint is observed due to elastic thermomechanical loading. This point is selected on the basis of Figs. 10, 11, 12, and 13 and is shown in Fig. 3. Shear displacement at this point is plotted against temperature of the slope surface. As the temperature of the surrounding slope surface is increased from 0 to 13.15 °C, shear displacement is also found to be increased from a minimum value of 0 mm to maximum values of 0.71, 0.72, 0.96, and 0.8 mm, respectively, for the slope surface temperature of 13.15 °C for all the four cases (crack filled with air, crack filled with water, crack filled with ice, crack filled with ice and water). Shear displacement at this point increases due to an increase in nonlinear thermal gradient. Normal stress along the joint is compressive in nature and is increased with increase in temperature due to elastic thermomechanical coupling of rock. Similarly, shear stress along the joint also increases with temperature, and it tends to move the upper block in a downward direction. In addition, shear strength along the joint is estimated according to the Mohr-Coulomb criteria assuming constant cohesion and friction angle along the joint with temperature. Moreover, the factor of safety is obtained from shear strength and induced

Fig. 10 Variation of shear displacement along the joint with the surrounding temperature when the crack is filled with dry air

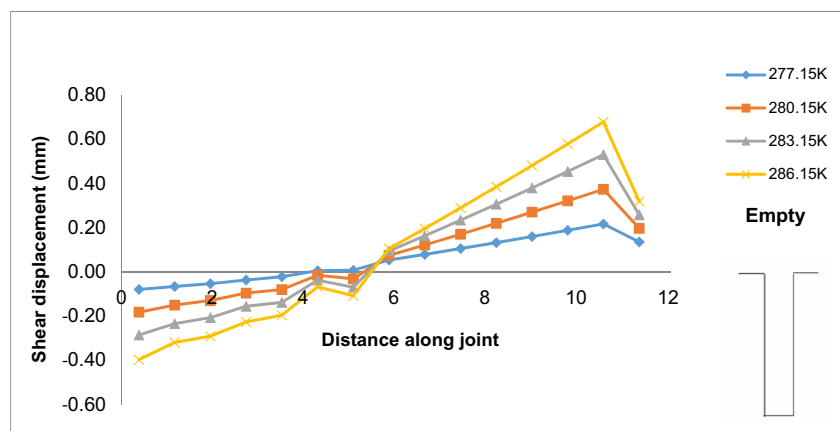
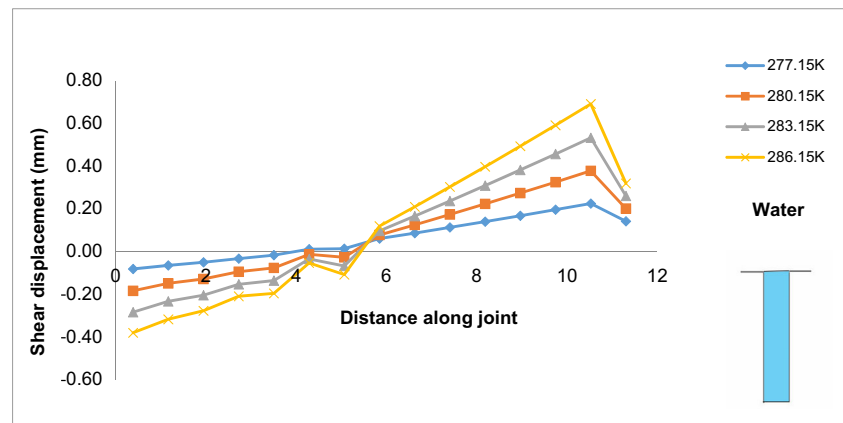


Fig. 11 Variation of shear displacement along the joint with the surrounding temperature when the crack is filled with water



shear stress. The value of induced normal and shear stresses along the joint depends on the orientation of discontinuity and also on the applied surface temperature field. Due to an increase in temperature, shear stresses along the joint also increase which can lead to progressive failure of rock slope along weakness planes. Due to an increase in temperature, normal stress along the joint also increases which leads to a higher value of shear strength, although the stability of the rock slope is determined by temperature-dependent values of driving and resisting forces (Fig. 14).

Comparison of results in different cases of infillings

Comparison of normal stress along the joint with the surrounding temperature in the four cases is shown with the help of graphs in Fig. 15. From the analysis, it can be easily seen that thermal effects are dominant than mechanical effects in terms of stress and displacement. When ice is filled in the crack due to phase change (ice to water), heat is absorbed from the surrounding rock and then heat is transferred by water through convection from the crack walls. In this case, a higher amount of heat is absorbed by infilling material from the surrounding rock medium. Therefore, in this case, there is a

higher amount of temperature drop along the joint as compared to other cases of infilling material in the crack. Due to a higher value of temperature gradient, in this case, higher value of induced stresses can be observed and, hence, higher value of normal stress along the joint. When the crack is filled with water and ice, less amount of heat is absorbed than in the case when the crack is filled with ice, but more than the case when the crack is filled with water or air. Therefore, less value of normal stress is induced in this case along the joint than the case when the crack is filled with ice but more than the cases when the crack is filled with water and the crack is filled with air. According to the values of normal stress along the joint, shear strength along the joint can be calculated from the Mohr-Coulomb criteria from Eq. 1. As normal stress increases with temperature, shear stress also increases with temperature, and this pattern can be observed in the four cases from the graph of normal stress vs. temperature (Fig. 16). Factor of safety depends on shear strength and induced shear stress along the joint (Fig. 17). Shear displacement and stress values along discontinuities are different depending on discontinuity orientation and location and are similarly variable along a single discontinuity. Thus, the results demonstrate that the magnitude of TM effects is essentially defined by model geometry

Fig. 12 Variation of shear displacement along the joint with the surrounding temperature when the crack is filled with ice

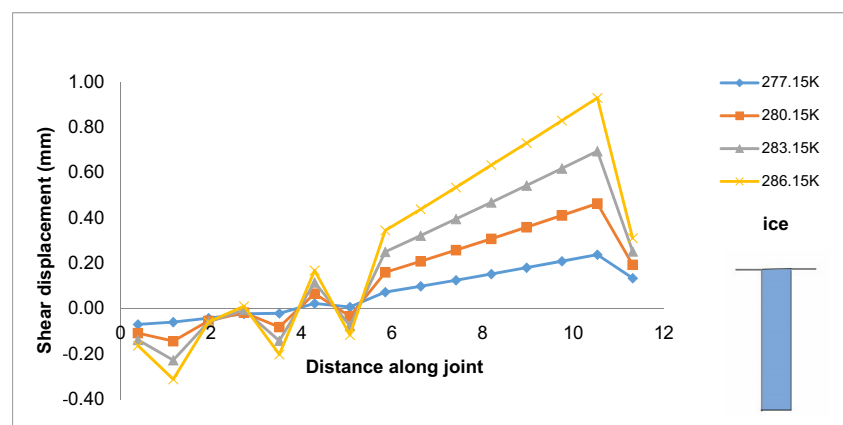
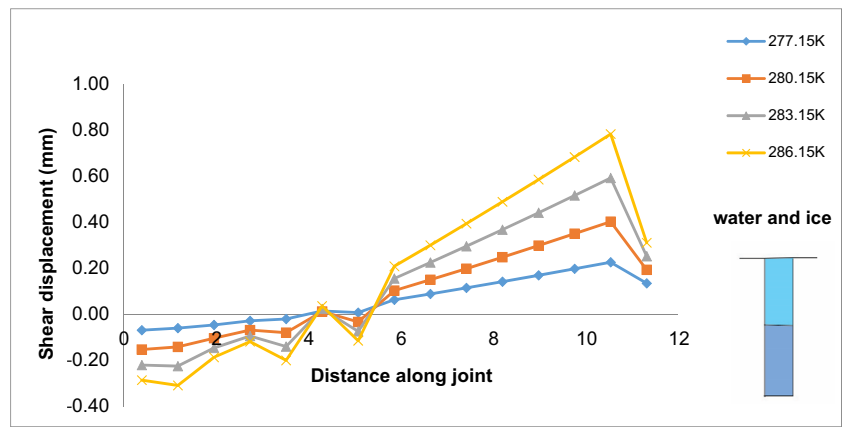


Fig. 13 Variation of shear displacement along the joint with the surrounding temperature when the crack is filled with ice and water



and discontinuity orientation. Therefore, factor of safety which is a function of induced shear stress along the joint also depends on discontinuity orientation. Induced shear stress also depends on the load due to gravity and force applied by the material in the crack. A high value of shear stress relative to normal stress in the case of water with ice is due to hydrostatic pressure of water and a high amount of heat transfer (phase change and convection) between the rock surface and fluid in the crack. The pattern of shear displacement in the four cases can be compared by the argument that the higher the value of temperature gradient, the higher will be the thermal expansion of the material and hence the larger will be the shear displacement.

may increase faster than the value of normal stress and failure may occur during warming (transition from winter to summer).

Mufundirwa et al. (2011) have shown that when the temperature of the rock slope increases, fractures tend to close because of the higher temperature of an outer strip of crack which causes thermal expansion resulting in fracture closure. In this study, also from Figs. 10, 11, 12, and 13, it can be observed from a negative value of shear displacement that as the temperature of the surface of the slope increases upward, lateral movement of the joint upper wall takes place resulting in crack closure.

Validation of results

In this study, the value of normal stress increases with the increase in temperature of the surrounding of the slope surface as shown in Fig. 15 for all the four cases. Gischig et al. (2011a, b) have shown that the magnitude of shear and normal stresses along the joint increases with the increase in temperature, after a minimum temperature is reached, and the value of shear stress

Conclusion

The present study shows the influence of the rise of temperature on the stability of jointed rock slope containing crack filled by different infilling materials (dry air; water; ice; water and ice) in the upper surface of the slope. This approach is based on a well-known relationship between shear strength and shear stress, shear strength properties, heat transfer due to conductive and convective processes, mechanical model by Krautblatter et al. (2013), and nonlinear 2D FE simulation. After the winter season, when

Fig. 14 Variation of shear displacement at the monitoring point with the surrounding temperature when the crack is filled with dry air (empty), when the crack is filled with water, when the crack is filled with ice, and when the crack is filled with water and ice

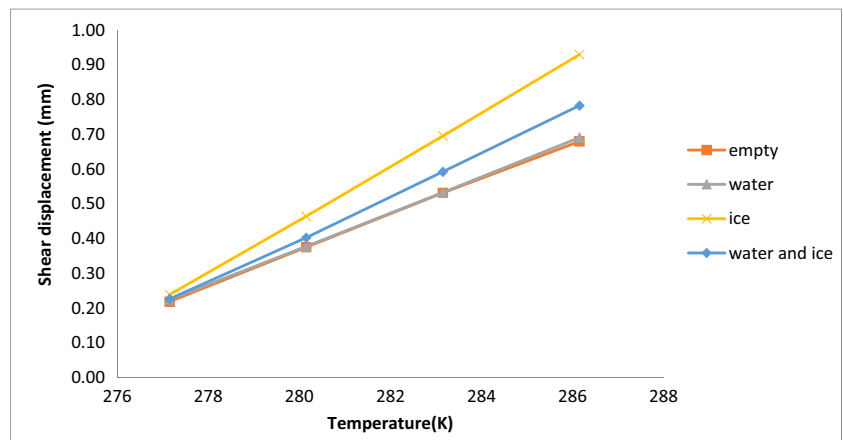


Fig. 15 Variation of normal stress along the joint with the surrounding temperature when the crack is filled with dry air (empty), when the crack is filled with water, when the crack is filled with ice, and when the crack is filled with water and ice

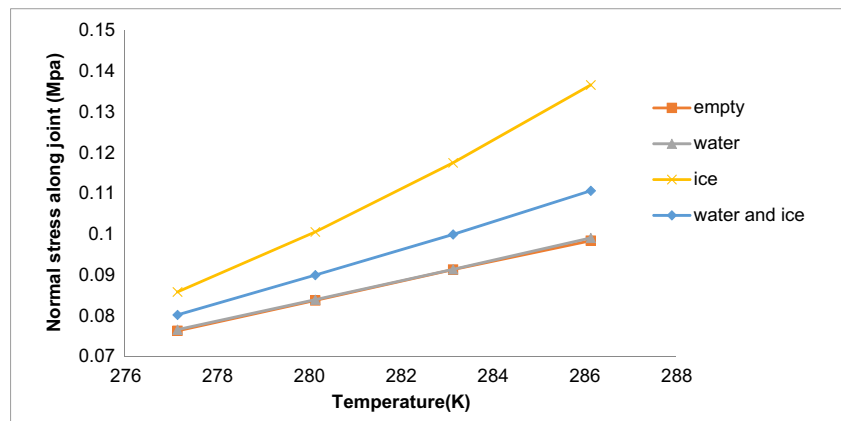
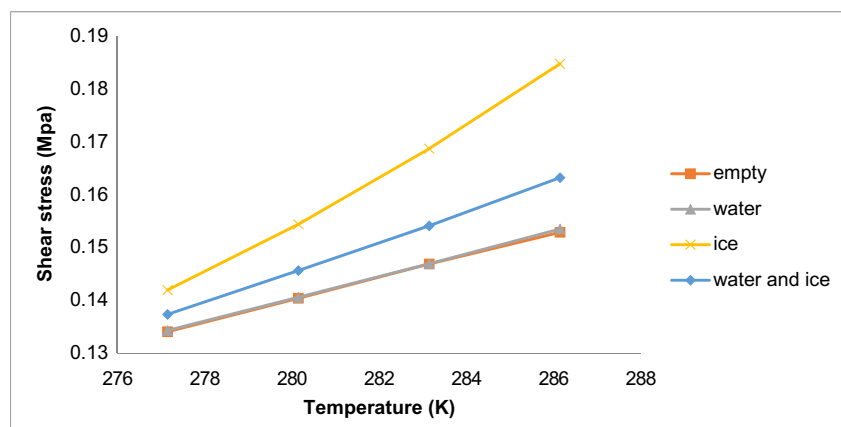


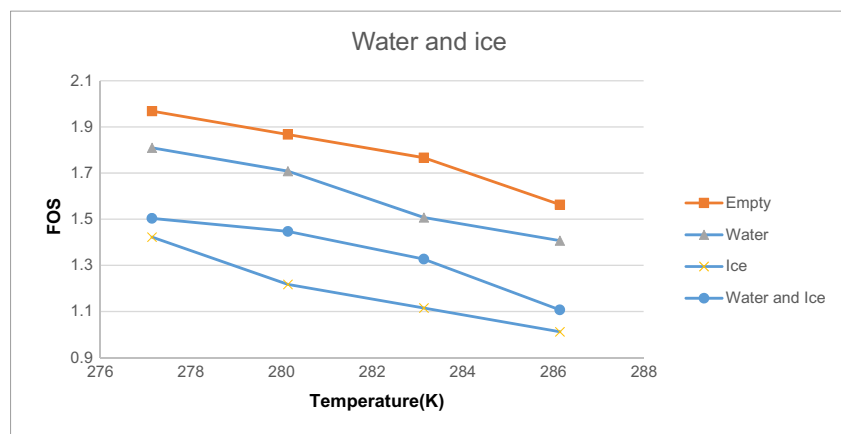
Fig. 16 Variation of shear stress along the joint with the surrounding temperature when the crack is filled with dry air (empty), when the crack is filled with water, when the crack is filled with ice, and when the crack is filled with water and ice



the temperature of the surrounding environment increases from subzero temperature, instability along the joint occurs because of shear stress induced by thermal gradients (due to convective and conductive heat transfer) that exist in rock mass. Although shear strength along the rock joint may increase due to increase in normal stress (according to the Mohr-Coulomb criteria) by thermomechanical effects, the overall stability of the jointed rock slope depends on the magnitude of both shear resistance and

shear stress along the joint. In this study, shear stress induce faster than shear resistance during warming of the slope, and hence, factor of safety decreases with increase in temperature. When ice is converted into water, hydrostatic pressure builds up on the walls of the crack, and a large amount of heat is transferred during phase change (absorbed from the surrounding rock surface). Therefore, high-magnitude temperature gradient is induced along the joint because of a large amount of heat transfer due to

Fig. 17 Variation of factor of safety for the joint with the surrounding temperature when the crack is filled with dry air (empty), when the crack is filled with water, when the crack is filled with ice, and when the crack is filled with water and ice



phase change. As a result of this, high-magnitude shear stress is induced along the joint in the case of ice as compared to other cases of infilling material which further cause instability in the rock slope. On the other hand, shear stress along the joint is found comparatively higher when water is filled in the crack than the case of air as an infilling material in the crack. The reason behind this fact is that water has a higher value of convective heat transfer coefficient as compared to air which causes high temperature gradient and hydrostatic pressure when the surface crack is filled with water as compared to the case of air.

As the temperature of the slope surface increases from 0 to 13.15 °C, shear displacement along the joint is also found to be increased from a value of 0 mm to values of 0.71, 0.72, 0.96, and 0.8 mm, respectively, for the slope surface temperature of 13.15 °C for all the four cases (crack filled with air, crack filled with water, crack filled with ice, crack filled with ice and water). The maximum value of horizontal tensile stresses caused by mechanical and thermal effects is in the range of 0.78–1.57 MPa at slope surface temperatures of 13.15 °C, respectively, for the four cases (crack filled with air, crack filled with water, crack filled with ice, crack filled with ice and water). Maximum value of vertical compressive stress through the domain is in the range of 15.3–15.4 MPa, for the four cases (crack filled with air, crack filled with water, crack filled with ice, crack filled with ice and water) at 13.15 °C temperature of exposed slope surface.

The thermomechanical effects which affect the stability of jointed rock slopes are highly dependent on orientation of discontinuity, joint strength properties, and infilling material present in the surface crack. According to the infilling material in the crack, the stability of the rock slope for the given geometry of slope is found in the following order: crack filled with ice < crack filled with ice and water < crack filled with water < empty crack. This sequence of stability has been examined on the basis of shear displacement evaluated at the monitoring point and factor of safety along the joint in the present study. The order of stability given above depends upon the amount of heat transferred from the rock mass to the infilling material.

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